Radiolytic influence on the surface composition of the Galilean satellites

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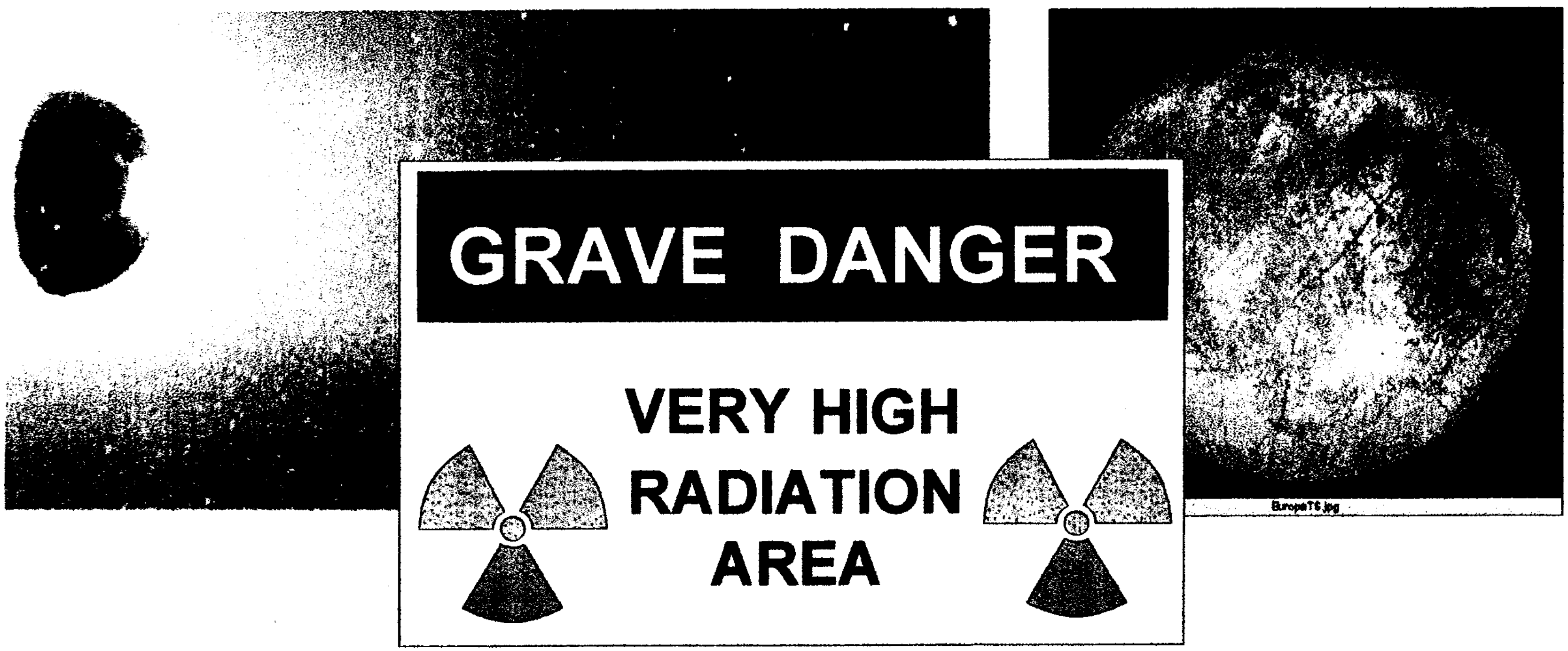


Radiolytic Processes on Europa

Europa is immersed in an intense **high-energy radiation** environment:

- the surface **chemical composition** is **altered** by **radiolysis** from energetic electron and ion bombardment
- Importance of radiolysis shown by presence of H_2O_2 and O_2 on Europa (*1,2*)
- Chemical **lifetimes** are **short** compared to geological time scales
- **Ion implantation** from the jovian plasma provides chemically reactive **sulfur**

The surface of **Europa** contains a **hydrated compound**

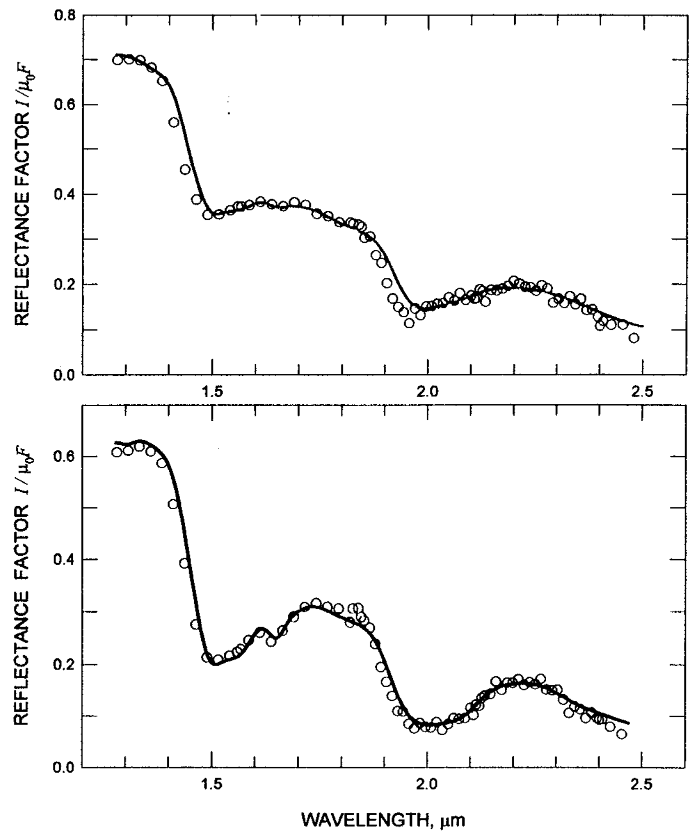
- producing distorted H_2O bands observed in *Galileo* NIMS spectra
- The hydrate was suggested to be radiolytically-produced **hydrated sulfuric acid**, $H_2SO_4 \bullet nH_2O$ (*3*)

In this work we discuss:

- our **spectral fits** using newly measured optical constants
- sulfur **radiolytic reactions** and new measurements
- The **observed distribution** of hydrate on Europa
- Compare observations with **predicted concentrations** from implantation and gardening

SPECTRAL FITS - 1

- **Previous fits** (*3*) were based on **diffuse reflectance measurements** of pure sulfuric acid octahydrate and hemi-hexahydrate (their spectra are identical)
- For comparison to Europa spectra, we recently **measured** the transmission of $H_2SO_4 \bullet 8H_2O$ to obtain the **optical constants** $n + ik$
- Spectral fits were obtained using **radiative transfer** theory for intimate granular mixtures and water ice (*4*)
- Two **example fits** are shown. The top spectrum is for 82% (by volume) acid, with acid and ice grain sizes of 31 and 30 μm, respectively. The corresponding parameters for the bottom spectrum are 42%, 41 μm, and 104 μm.

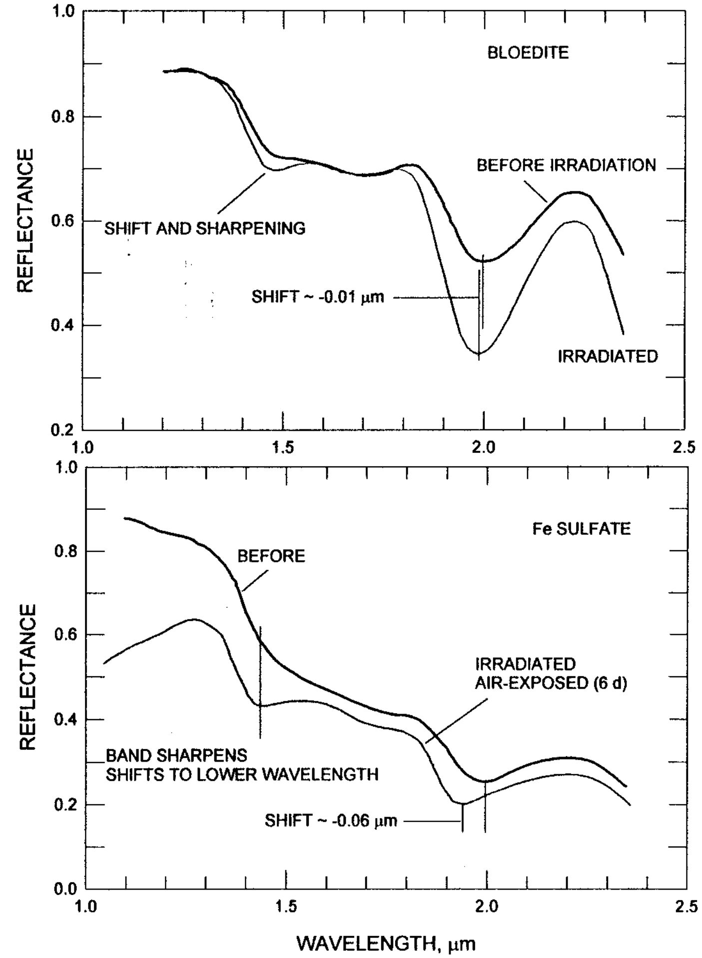


SPECTRAL FITS - II

The fits to Europa spectra are encouraging, except at the **short-wave band edges**, where **Europa's absorption profile is sharper and shifted** to shorter wavelengths (by ~ 0.01 to 0.02 μm).

These spectral differences are **similar to changes observed in proton-irradiated** and **radioactive sulfates** (*5,6*) due to radiolytic removal of loosely-bound H_2O *(7)* (similar shifts are seen in thermal dehydration) and production of defects that break symmetry and cause bands to broaden.

The Figure shows spectral alterations from **proton irradiation** equivalent to < 5 y on Europa (*5*). Band shifts of 0.01 to 0.06 μm are found, as well as band shape changes. **Similar** shifts and shape **changes** are **expected** for H_2SO_4 and other hydrates on Europa.



THE RADIOLYTIC SULFUR CYCLE – 1

Radiolytic equilibrium produces a surface composition that is **self-healing**, with a **dynamic equilibrium** of production and loss.

The major chemical reservoirs in the radiolytic **sulfur cycle** are **sulfur** (S and S_x), **sulfur dioxide**, and hydrated **sulfuric acid** $H_2SO_4 \bullet nH_2O$, $n = 6.5, 8$, (actually oxonium sulfate hydrate).

Production of sulfuric acid is principally:

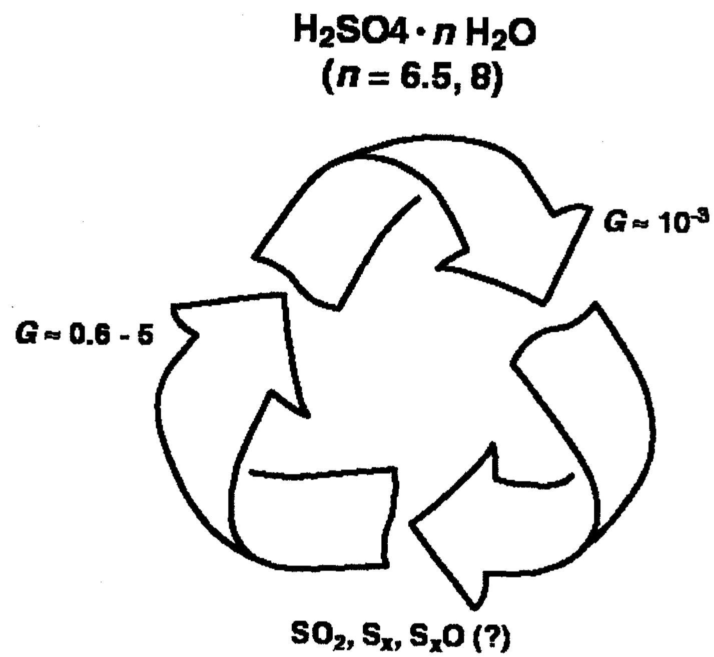
1) $S, S_x + H_2O \rightarrow H_2SO_4 \bullet nH_2O$
2) $SO_2 + H_2O \rightarrow H_2SO_4 \bullet nH_2O$

And the acid is **destroyed** as

3) $H_2SO_4 \bullet nH_2O \rightarrow S, SO_2, \ldots$

Efficiencies of radiolytic reactions are often expressed as "***G*-values**", the number of molecules made (or destroyed) per 100-eV of absorbed energy. We summarize below current knowledge of these reactions and their efficiencies, and report new measurements.

THE RADIOLYTIC SULFUR CYCLE



THE RADIOLYTIC SULFUR CYCLE – II

$$S, S_x + H_2O \rightarrow H_2SO_4 \bullet nH_2O$$

Irradiated suspensions of **sulfur** in liquid **water** are known to rapidly produce **sulfuric acid** (*8*), but reactions in the frozen state were not determined. We measured the production of sulfuric acid for a 2% $[S]/[H_2O]$ suspension at 77 K using electrons produced from Co^{60} γ-rays. We found $G(H_2SO_4) = 0.01$. Using the ionizing energy flux in the optical layer of Europa's surface (*9*), the **lifetime** for S atom conversion to sulfuric acid is **30 years**.

$$SO_2 + H_2O \rightarrow H_2SO_4 \bullet nH_2O$$

Radiolysis of pure, **frozen SO_2** produces mainly **SO_3**, with $G = 5$, along with sulfate and elemental sulfur *(10)*. SO_3 reacts very rapidly with H_2O to **form H_2SO_4**, so the reaction lifetime in the optical surface layer is ~ **5 years**. Radiolysis of SO_2/H_2O mixtures will be studied in 2001.

$$H_2SO_4 \bullet nH_2O \rightarrow S, SO_2, \ldots$$

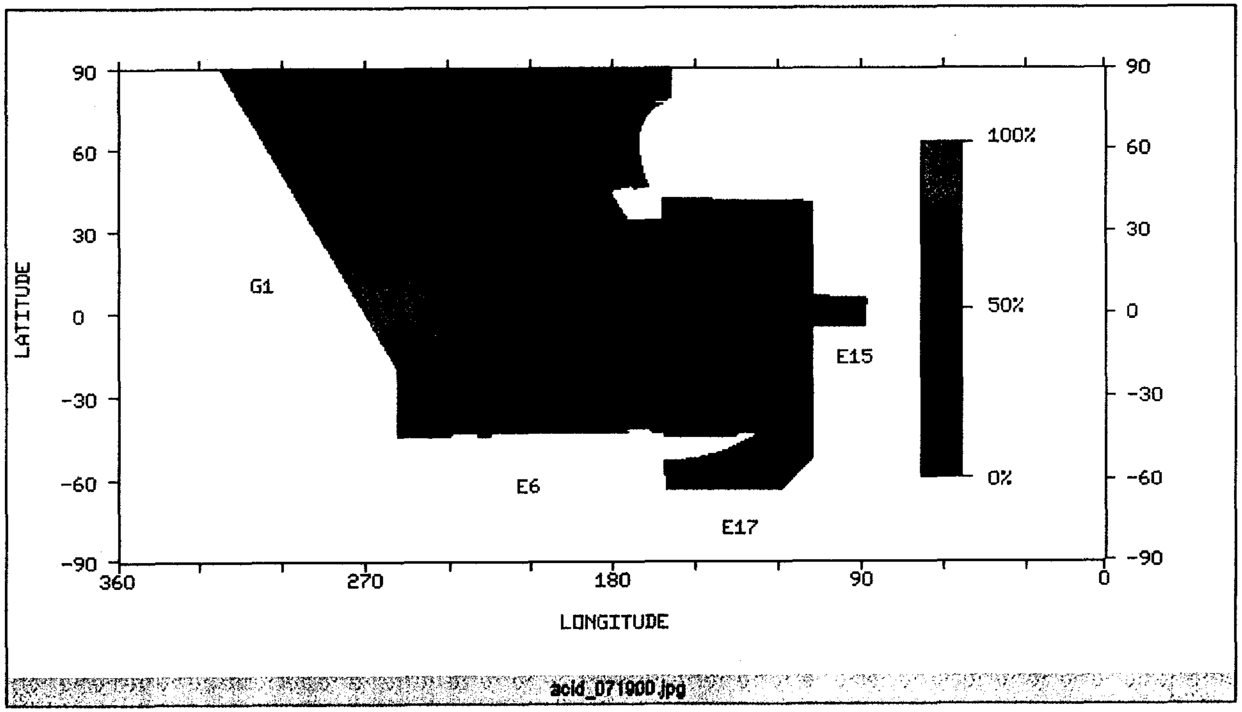
Sulfates are decomposed by ionizing radiation, but they are among the more radiation resistant chemical compounds. The cations (H, Na, Mg, etc.) can be removed, and sulfate is dissociated to SO_3^-, followed by eventual formation of SO_2, S, and sulfide (e. g. H_2S)*(11, 12)*. The **sulfates** are **more stable when hydrated,** and typically $G \sim 0.005$. The lifetime of hydrated sulfuric acid in Europa's optical layer (and generally any hydrated sulfate) is ~ **1000 to 2000 years**. The primary radiolysis product is sulfur dioxide and oxygen, with S and H_2S each being ~ ¼ of the SO_2 production *(11)*.

DISTRIBUTION OF HYDRATE ON EUROPA

The initial **source of sulfur is hidden** by ensuing radiolysis events, but the **surface distribution** of hydrated sulfuric acid **may provide a clue** to its origin. Source candidates include 1) ion implantation, 2) micrometeoroid infall, and 3) endogenic sources of sulfurous material [e. g. evaporite salts (*13, 14*) and sulfur dioxide (*14*)]

We used NIMS data and an emperical method (the ratio of radiances at 1.5 and 1.8 μm) to find the hydrate distribution. We verified the method using detailed radiative transfer fits.

Note the strong **trailing side enhancement** in the distribution map, suggestive of ion implantation.



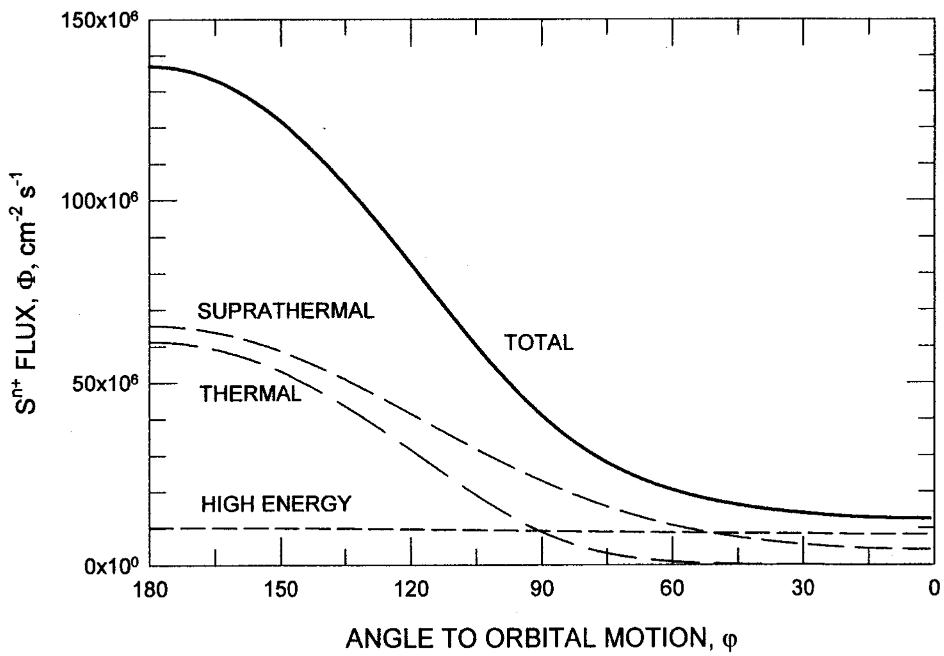
Predicted Distribution Compared to Measurements - 1

The hydrate distribution is influenced by the source, the pattern of radiolysis, and sulfur removal processes such as gardening. Europa may be rotating asynchronously and this would modify exogenic influences.

The **equatorial distribution of ion implantation** (at right), for synchronous rotation, shows that a I-cm thick deposit would be accumulated on the trailing side in 10^7 years, and ~ 1/10 of that on the leading side.

Micrometeoroid infall would show the opposite asymmetry, with more accumulated on the leading hemisphere. This source is < 1% of the sulfur ion implantation rate.

Sulfur implantation fluxes on Europa



Since the observed amount of sulfur can be accumulated in just 30,000 years, **some process must be removing surficial sulfur.**

Predicted Distribution Compared to Measurements – II

Gardening by micrometeoroid impacts will **bury** the accumulated sulfurous material. This process also **increases** the trailing/leading **asymmetry**, but **asynchronous rotation will reduce the contrast**. The Figure shows the measured equatorial distribution and predictions for synchronous and asynchronous rotation and three micrometeoroid impact asymmetry parameters, $\alpha = 0, \frac{1}{2}, (\frac{1}{2})^{1/2}$, ($\alpha$ is the ratio of the orbital velocity to the collision velocity and is expected to be ~ 0.6, Ref. *9*).

The top panel shows the unlikely $\alpha = 0$ case (uniform gardening) to illustrate the averaging effect of asynchronous rotation. The trailing/leading ion implantation asymmetry is reduced to ~ 1.5. Impact gardening [through a factor $(1 + \alpha \cos\theta)^{2.2}$] (*15*) contributes additional asymmetry, and the two bottom panels represent plausible extremes. The middle panel ($\alpha = \frac{1}{2}$) shows **consistency with asynchronous rotation** with period P ~ 2 My, while the bottom panel is consistent with P ~ 0.1 My.